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Research Requirements to Reduce Civil Helicopter Life Cycle Cost

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ABSTRACT

This report documents how life cycle costs of civil helicopters can be reduced through the application of existing technology, and how the costs of future helicopters may be reduced through applied research and development. The problem of high helicopter costs is defined and cost drivers are identified. The technological and management deficiencies which contribute to high costs are explained, and basic research and development projects which can reduce costs are enumerated.

CLASSIFICATION

FOREWARD

This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was NASA Program Manager for these studies. The Boeing Project Manager was Kenneth T. Waters.

CLASSIFICATION

SUMMARY

This study provides substantiation for the premise that helicopters are more expensive to buy and operate, than are fixed-wing aircraft. Using the results of surveys performed by the University of Virginia in another study, and the Boeing Vertol Company in this study, it was affirmed that civil helicopter operators are concerned about these costs. The operators put direct operating costs as number 1, and helicopter initial costs as number 3 in a ranking of 8 factors where technological improvements could most aid their operations. An average distribution of civil helicopter operator life cycle costs is as follows:

Acquisition	32.0%
Flight Personnel	20.5%
Fuel	11.1%
Insurance	6.4%
Maintenance	30.0%

A more detailed breakout shows that four areas account for about 50% of life cycle cost: flight personnel, fuel, engine maintenance (turbine), and airframe structure production cost. As discussed in the report, there is little that can be done to reduce the cost impact of pilot salaries, however, most of the other areas can have their costs reduced in two ways. First, based on technology typified by the newer generation of helicopters such as the AS 350, S-76 and B-222 and other available technology, life cycle costs should be about 17% lower. Secondly, as a result of improvements which could result from the research programs recommended in this study, life cycle costs could be reduced by almost 30%, compared to the existing civil helicopter fleet. This research falls into seven categories, listed below:

1.	Reduced Fuel Consumption	$144 Million	7 years
2.	Engine R&M	$100,000*	1 year
3.	Airframe Production Cost	$2 Million	5 years
4.	Engine Production Cost	$3 Million	5 years
5.	Safety	$7.6 Million	4 years
6.	Rotor System Production Cost	$2 Million	3 years
7.	Advanced Transmission	$9 Million	7 years

*Additional research to be defined from this program.

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1.0 INTRODUCTION

The helicopter is one of man's most remarkable inventions. Not only can it fly like a conventional airplane, but it can take off and land vertically, and hover stationary in mid-air. These unique capabilities make it an ideal vehicle for transportation to remote places or for avoiding airports, and for special tasks requiring the delivery and placement of heavy or bulky items through the use of an external cargo hook. Generally, for passenger trips of less than 300–500 miles, the helicopter is the vehicle of choice over an airplane, when time is of prime importance. This is due to its capability of offering literally door-to-door service. Charter operators report that when a helicopter is requested by a customer, it is frequently required on short notice, indicative of its time value. The helicopter is also used almost exclusively for transportation of crews to and from offshore oil platforms. In industrial use the helicopter is popular for the placement of utility line towers, building rooftop heating and air conditioning units, and in timber logging operations. Figure 1 shows the distribution of helicopter flying hours by type of use.

Naturally, it is to be expected that remarkable inventions cost more than others, and the conventional wisdom is that helicopters are more expensive than fixed wing aircraft. This is due to the increased amount of machinery and mechanisms required in the transmission of power from the engine to the rotor blade. This increased amount of hardware is found in the transmissions with their large number of gears and bearings, the drive shafts, and the rotor hubs, blades and controls.

1.1 Acquisition Cost

Helicopter costs can be evaluated in many ways, but the two primary criteria are acquisition cost and operating cost. The 1978 Planning and Purchasing Handbook published by Business and Commercial Aviation Magazine (reference 2) was used as the source document for a comparison of helicopter and fixed wing acquisition costs. The helicopter data used in this analysis was comprised of the base prices of nine piston helicopters, seven single-engine turbine helicopters and eight multi-engine turbine helicopters, for a total of 24 data points. The airplane data consisted of the base prices of 18 single-engine aircraft, 11 multi-engine piston aircraft and 14 turboprop aircraft, for a total of 43 data points. Turbocharged, pressurized and turbojet/turbofan aircraft were not included in the analysis, since they represented optional-type features which increased the base prices of the aircraft without increasing the number of passenger seats available. A regression analysis was performed which correlated base price with number of passengers that could be carried. This parameter was one of several which could have been chosen, such as passenger miles per hour, but if passenger miles per hour were used, then the fixed wing aircraft would have benefited since they can generally fly faster. This would have required the computation of "door-to-door" time, in order to put the helicopters on a par with airplanes, and would have made the analysis unnecessarily complex. Figure 2 shows the resulting regression lines for base price as a function of the number of passenger seats. Based on this analysis, it appears that for aircraft with less than eight passenger seats, fixed wing aircraft are generally less expensive to buy than helicopters. Most helicopters fall into this

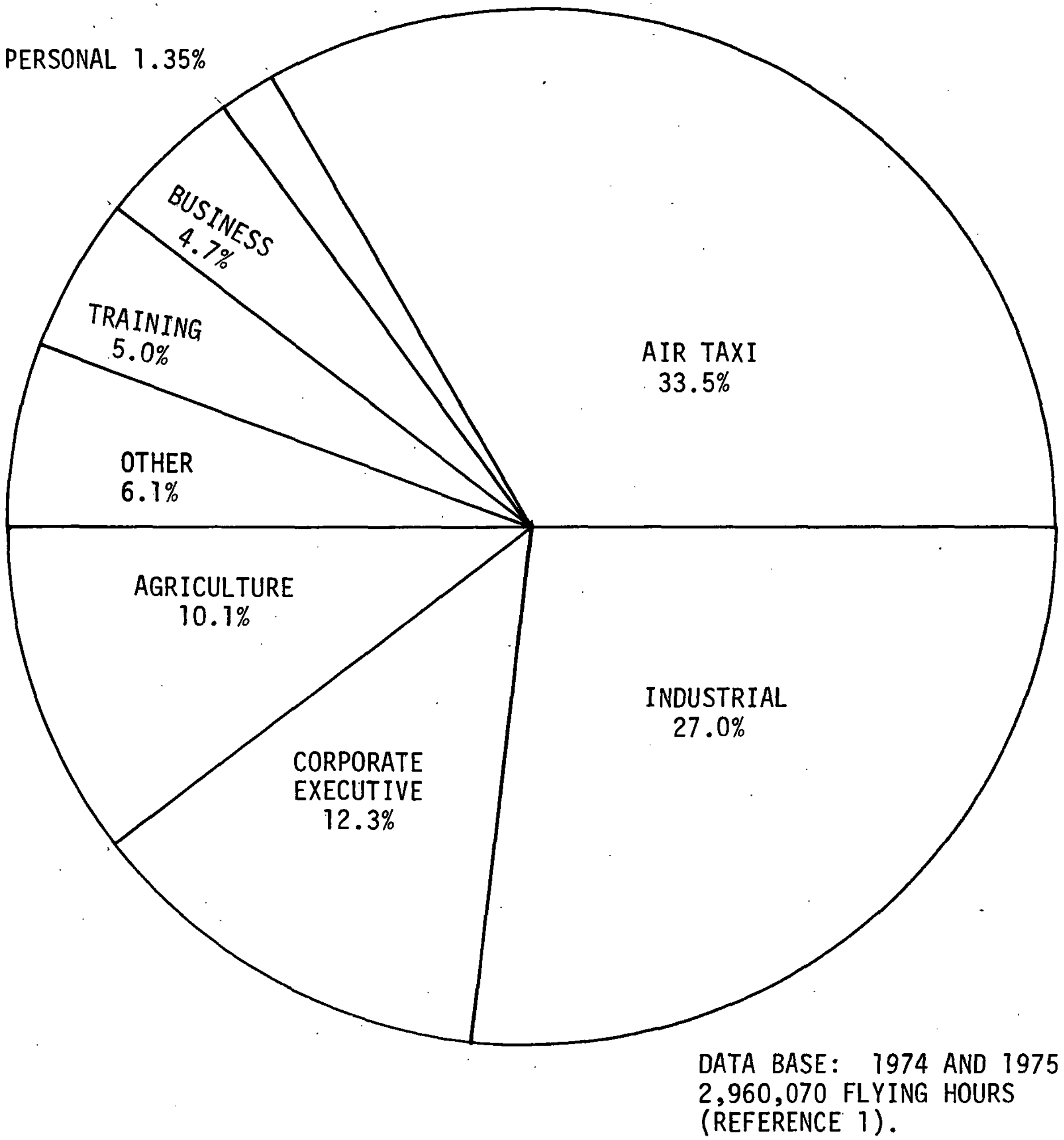

Figure 1. Percentages of civil helicopter flying hours by type of flying

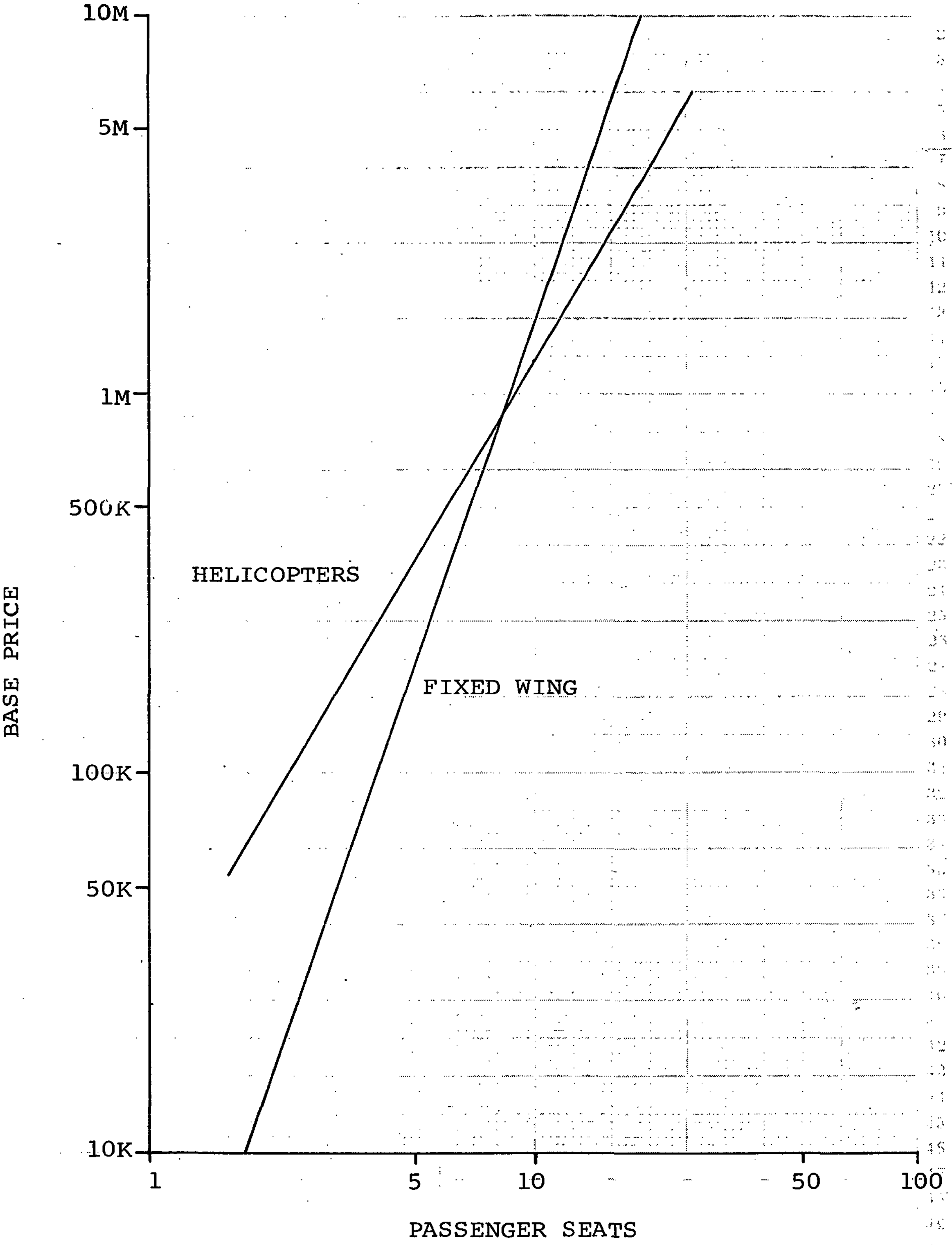

Figure 2. Passenger seats versus base price

category. For aircraft with more than eight passenger seats, helicopters are less expensive than fixed wing aircraft. It should be pointed out that there is a large spread in prices for any given number of passenger seats, especially for airplanes, and there are cases, for example, where a four passenger helicopter can cost less than a four passenger airplane. However, Figure 2 does illustrate a general relationship.

The source data was again analyzed, and this time a regression analysis was performed which correlated base price with useful weight. Figure 3 shows the resulting regression lines for base price as a function of useful weight. This figure clearly shows that for any given amount of useful weight, fixed wing aircraft are less expensive to buy than helicopters, and supports the popular opinion of high helicopter cost.

1.2 Operating Cost

The second parameter for evaluating helicopter economics is operating cost. Data to support the hypothesis that helicopters are more expensive to operate than airplanes is slightly more difficult to gather. Aircraft manufacturers readily publish base prices for their products and in many cases operating costs. However, due to the manufacturer's inherent bias for his own product, and the fact that different techniques for calculating operating costs may be used, manufacturers' estimated operating costs are not suitable for use.

A traditional source of operating cost data is the U.S. military, but care must be taken to insure that consistent methods of calculation were used, and this can be difficult when data from different branches of the military are used. Figure 4 shows a comparison of operating costs per flight hour based on U.S. Army field experience. Helicopters are compared with fixed wing aircraft on a dollars per flight hour versus aircraft weight empty basis. All of the data were taken from the U.S. Army Aviation Planning Manual (reference 3), and the costs include field and depot parts and labor, and POL (petroleum, oil and lubricants). Although these operating costs cannot be used in the absolute sense to represent civil helicopter costs, nevertheless the information does come from a single consistent source, and does show the relative difference in fixed wing and helicopter operating costs, with the helicopter being more expensive.

The ideal source for operating cost data is the operator himself, preferably an operator who charters both helicopters and airplanes so that the methods of operating cost calculation are consistent for both kinds of aircraft. However, most operators are reluctant to divulge operating cost data for competitive and other reasons, or if they do give operating costs they don't want them published. This is understandable. The next best thing then was to sample a few operators who charter both fixed wing aircraft and helicopters, and determine their rental prices. Although rental prices are based on both acquisition and operating costs, they are still a good indication of operating costs, since operating costs over the life of the aircraft are generally higher than acquisition costs. This point will be shown later in the report. Figure 5 illustrates the relationship between number of passenger seats and dollars per flight hour charged for rental. The data is based on a sample of three operators in different locations and with different operations, and shows that fixed wing aircraft are less expensive to rent than

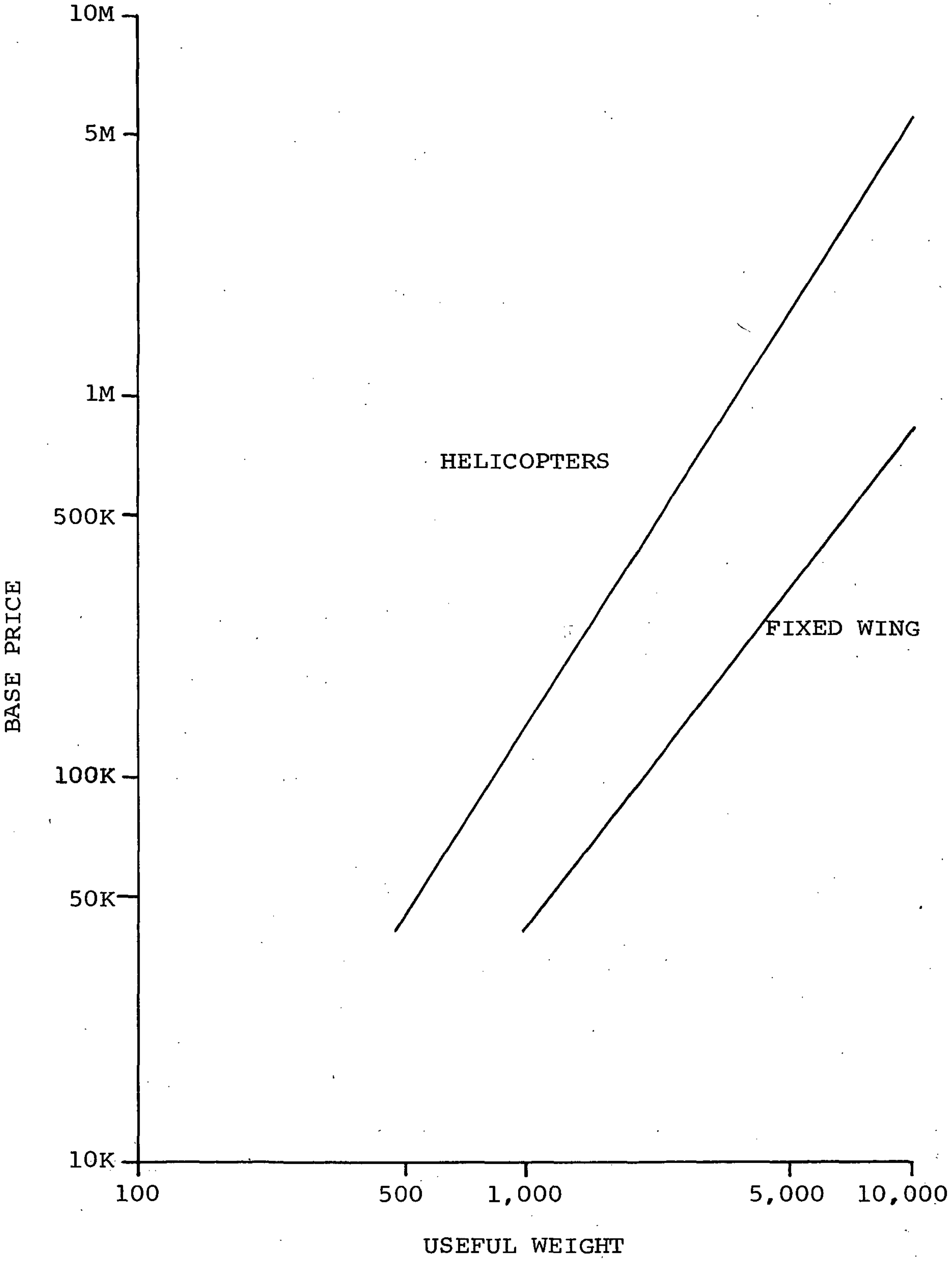

Figure 3. Useful weight versus base price

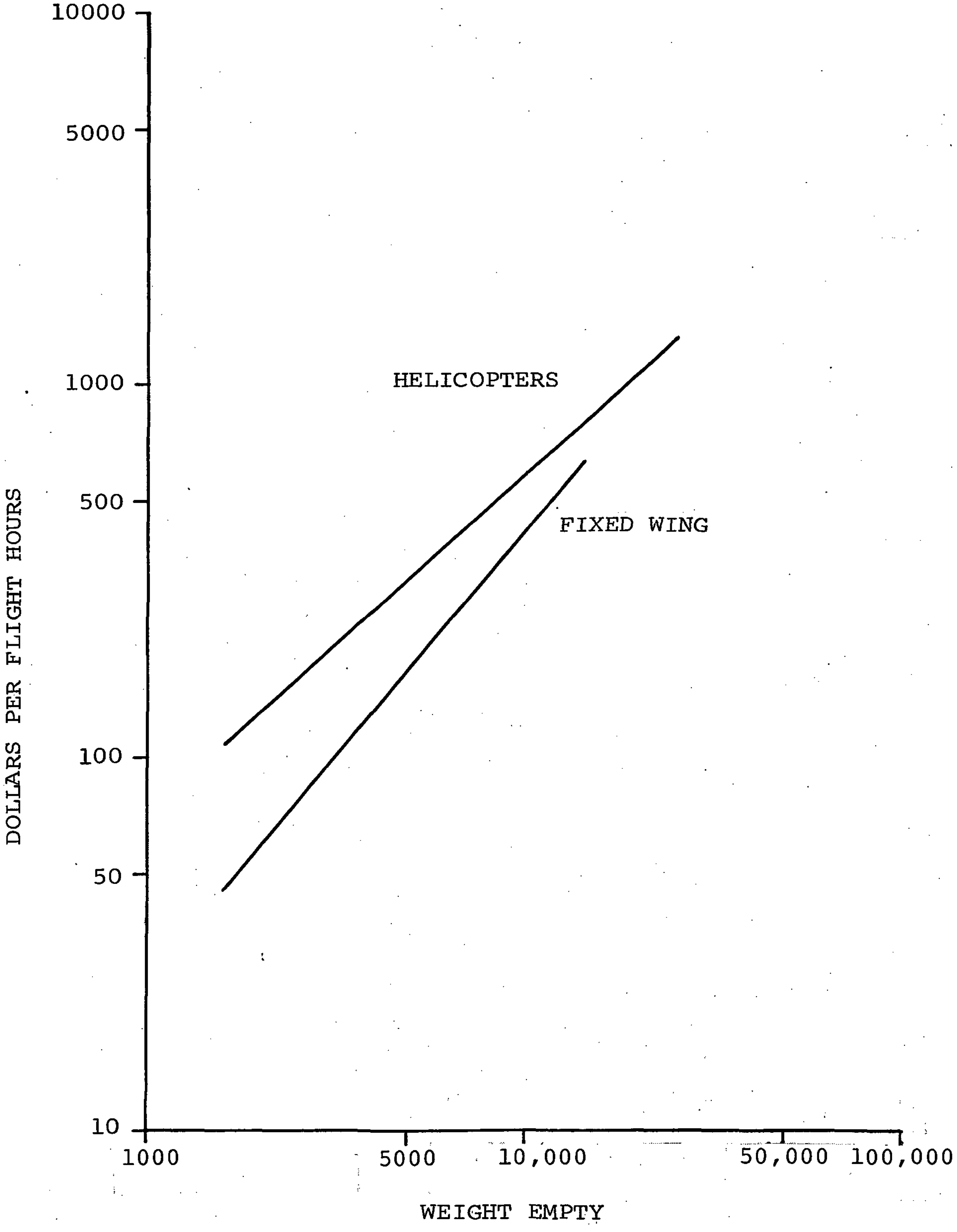

Figure 4. Weight empty versus operating cost

25%

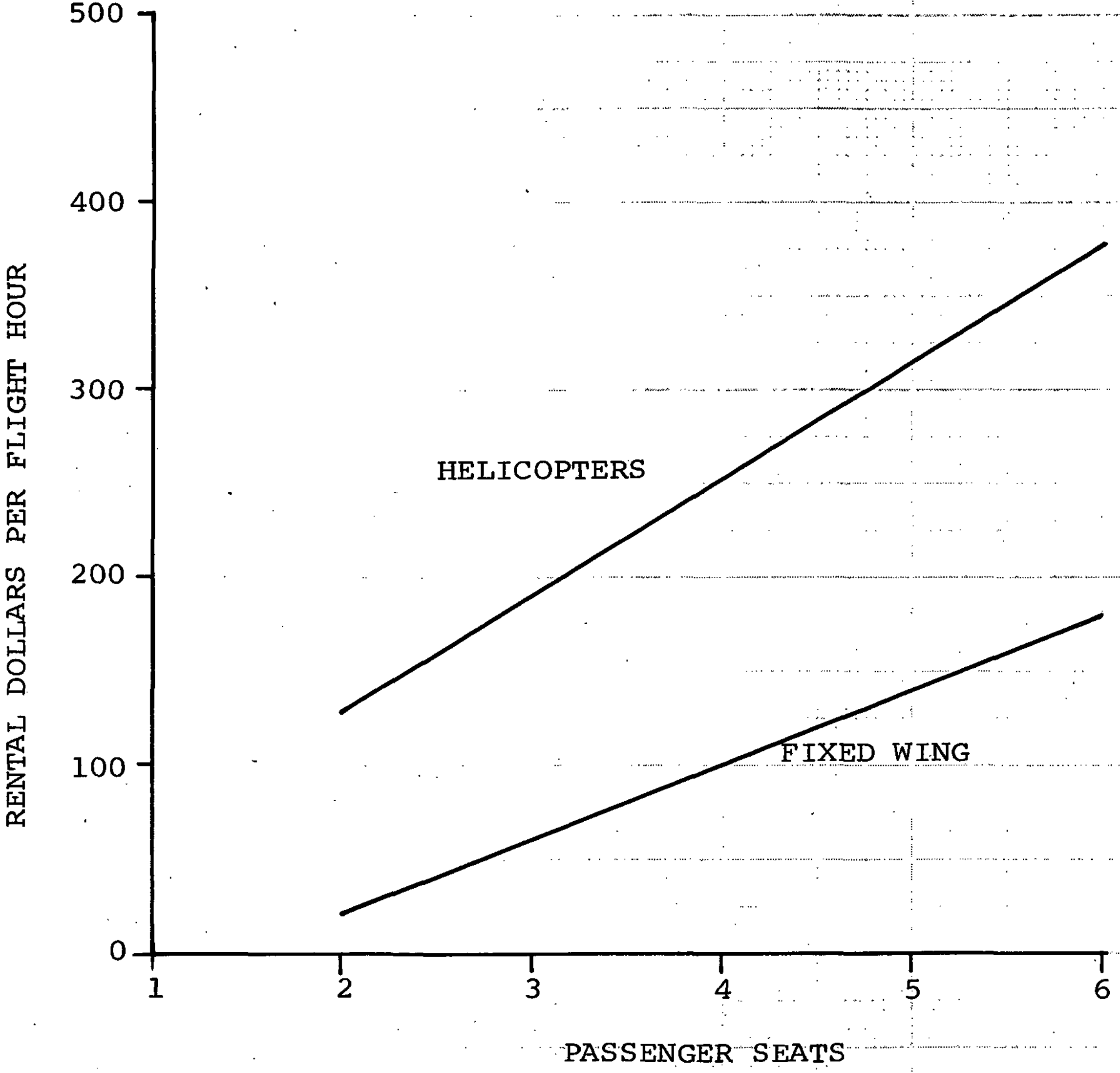

Figure 5. Passenger seats versus rental price

helicopters. Although the data considers only aircraft which carry six passengers or less, 90% of all helicopters operating in 1976 fell into this category (reference 4).

The previous sections supported the basic hypothesis that helicopters are more expensive to buy and operate than fixed wing aircraft. However, there are times and places when there is no possible fixed wing alternative to the helicopter. It would seem then that the helicopter's cost in these cases should be acceptable since it is the best or only way of getting the job done. Nevertheless, even operators who have these "helicopter only" kinds of work still complain about the high cost of the helicopter. The succeeding sections of the report shall explain why.

2.0 SURVEYS

In order to better define the problem of high helicopter costs and understand it from the operators' viewpoint, two operator surveys were used in this study. The first survey was taken by the University of Virginia in support of the development of a research project selection model (reference 5), and the second survey was based on a questionnaire developed by Boeing Vertol specifically for this project.

2.1 University of Virginia Survey

During 1976 a questionnaire was mailed to civil helicopter operators across the country in order to evaluate helicopter operations and to develop statistics which could lead to increased operator, passenger, and community acceptance of the helicopter. Twenty-four questions were asked, some of which applied to the problem of helicopter costs. Response to the survey was good in that completed questionnaires were returned by 61 commercial, 59 corporate and 43 civil government helicopter operators.

Question number 22 was concerned with passenger acceptance and asked the operator to determine on a scale of 1 to 7 whether little emphasis or major emphasis should be placed on four different approaches to increasing passenger acceptance of helicopters. The four were: reduce vibration, reduce noise, make costs more competitive with other systems, and increase system safety. The combined results showed that more operators felt that major emphasis should be placed on reducing noise than should be placed on the other three. However, a close second (168 versus 160) was to make costs more competitive with other systems. In question 23, operators were asked to rank the factors where technological improvements could most aid their operations. Out of eight factors, direct operating cost was ranked number one, and aircraft initial cost was ranked third. Table 1 shows the ranking of the 8 factors by each type of operator and combined. It is clear that cost is uppermost in the mind of the helicopter operator, but where are the costs most significant? It was not the purpose of this questionnaire to find out but the answers to certain other questions in the survey are helpful.

Question number 21 was concerned with performance considerations and asked the operator to determine on a scale of 1 to 7 whether little emphasis or major emphasis should be placed on six different approaches toward improving performance. The six were: greater range, increased maneuverability, more payload, more efficient power plant, increased speed and reduced fuel consumption. The combined results showed that reduced fuel consumption ranks fourth out of six as a factor on which major emphasis should be placed. Apparently the operators were not very concerned with fuel consumption.

The response to questions 12 and 13 give some insight into where operating costs are high and Table 2 shows these questions and their responses. The answers to questions 12 relate that scheduled maintenance is four times the unscheduled maintenance rate. This compares with the ratio of about 2 to 1 for U.S. Navy helicopters as shown in Research Requirements To

TABLE 1. RANKING OF FACTORS WHERE TECHNOLOGICAL IMPROVEMENTS COULD MOST AID OPERATIONS

Factor	Combined (163)	Corporate (59)	Commercial (61)	Civil Government (43)
Direct Operating Costs	1	3	1	3
Aircraft Performance	2	1	2	4
Aircraft Initial Cost	3	4	2	1
Aircraft Safety	4	2	4	2
Passenger Acceptance	5	5	5	7
Reduced Fuel Consumption	6	6	6	5
Community Acceptance	7	7	7	6
Improved IFR Capability	8	7	8	8

Reduce Maintenance Cost of Civil Helicopters (reference 6). The responses to question 13 show engines to be the number 1 maintenance area followed by the drive system, airframe and rotors. Although the distribution is slightly different, these four systems were the top four contributors to the failure rate and maintenance manhours as reported in Research Requirements To Improve Reliability of Civil Helicopters (reference 7).

TABLE 2. QUESTIONS 12 AND 13 AND THEIR RESPONSES

Question	Average	Corp	Comm'l	Civil Gov't
12. What % of your total maintenance is:				
Scheduled	78.0%	79.6%	79.5%	75.0%
Unscheduled	18.6%	15.3%	20.4%	20.0%
13. What % of your total maintenance is related to:				
Engines	27.3%	25.4%	26.4%	30.0%
Drive System	18.6%	18.9%	21.0%	16.0%
Airframe	18.3%	20.5%	18.4%	17.0%
Rotors	13.7%	12.2%	11.9%	16.0%
Avionics	9.1%	8.3%	10.0%	9.0%

The results of this survey confirmed that helicopter operators were concerned about direct operating costs and acquisition costs, that reduced fuel consumption was not that urgent when compared with other considerations, that scheduled maintenance accounts for 78% of all maintenance, and that engines and drive system account for 46% of all maintenance. The results of the next survey provide more detail on the helicopter cost problem.

2.2 Boeing Vertol Survey

A questionnaire was developed to gather information from the helicopter operators primarily in the cost area, but additional questions were added to assist in the safety, reliability, maintainability and requirements phases of this study (references 1, 6, 7, 8). The questionnaire was sent to 200 operators in the United States and Canada. Although only 36 surveys were completed and returned, these responses cover the operations of 510 aircraft thereby representing a sizeable sample. The questionnaire and the composite responses are shown on the following three pages. In all cases the responses shown represent the combined answers of all three types of operators, except for questions 3, 4 and 5, where the responses for the civil government operators are shown separately since they are so different from the commercial and corporate operators. The civil government responses represented the operation of about 70 aircraft. The responses to these questions differ significantly from the Army Helicopter Cost Drivers Report (reference 9), and show the danger in applying military data to civil helicopter

QUESTIONNAIRE

1. Our organization is primarily classified as a

23 (64%) Commercial Operator (air taxi, patrol, pollution monitor, agriculture, forestry, construction, resource exploration, etc.)

5 (14%) Corporate Operator (passenger transport, private use, photo, etc.)

8 (22%) Civil Government Operator (patrol, emergency, search and rescue, etc.)

2. How many helicopters do you operate? 510

Helicopter Type	No. of Aircraft	Average Annual Flt. Hrs./Aircraft
Bell 206	222 - 43.5%	802
Bell 47	119 - 23.3%	524
Bell 212	25 - 4.9%	1000
Hughes 500	18 - 3.5%	902
Sikorsky S-58	18 - 3.5%	553

3. What percent of your helicopter costs are spent on:

37 % Acquisition of the helicopters (including initial spares) Civil Gov't. - 5%

63 % Operations and support Civil Gov't. - 95%

4. Of your helicopter operations and support costs, what percent are spent on:

43.2 % Direct support maintenance (field and depot labor, and parts) Civil Govt. - 40.8%

17.2 % Consumables (fuel, oil, lubricants) Civil Govt. - 12.6%

28.3 % Personnel (salary and training for flight crews) Civil Govt. - 42.8%

10.7 % Insurance Civil Govt. - 3.3%

.6 % Other (please specify) Civil Govt. - .5%

5. Of your direct support maintenance costs, what percent are spent on:

49 % Labor Civil Govt. - 30%

51 % Parts Civil Govt. - 70%

6. What is the most important thing that could be done to reduce your helicopter costs?

1. Eliminate or extend TBO's - 20

2. Reduce parts cost - 12

3. Improve R&M - 11

What is the second most important thing that could be done to reduce your helicopter costs?

4. Reduce acquisition cost - 8

5. Reduce number AD's & SB's - 5

6. Reduce fuel consumption - 4

7. What are your major problems for

Safety? *1. Pilot related complaints - 9*

2. Operational problems - 6

Maintenance? *1. AD's and SB's - 7*

2. Parts and availability - 7

Reliability? *1. Avionics & electronics - 7*

2. Engines - 5

8. What are the components or parts of the helicopter you would like to see improved?

1. Rotor System - 23

2. Engines - 16

3. Drive - 16

9. What do you believe are the three most important characteristics that ought to be designed into future civil helicopters? (Such as, Power, Speed, Equipment, Safety, etc.)

1. Speed - 20

2. Power - 17

3. Safety - 15

4. R&M - 15

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10. What is the first thing you would change in this business if you had sole authority?

1. *The regulatory environment - 17*

2. *Manufacturers' attitudes - 7*

11. Any additional comments?

12. May we contact you by phone or in person for further discussion?

Person to Contact ______________________

Company ______________________

Phone Number ______________________

operations. The Army report shows acquisition costs to be 25% of total life cycle costs, and operating cost to be 75%. Of the operating cost, maintenance and parts are 75%, consumables are 15% and flight personnel are 10%. Disregarding insurance and the "other" category, the commercial responses were calculated to be 49%, 19%, and 32% respectively for the same categories. The U.S. Army labor/parts split for field labor was 70/30. Direct support maintenance then is the largest contributor to helicopter operations and support costs for the commercial operators. While personnel represent a significant amount and consumables is not small, these costs are apparently accepted by the operator as a cost of doing business, since personnel is not mentioned in question 6 as a potential cost reduction item, and fuel consumption is mentioned infrequently.

The numbers shown next to the responses to questions 6 through 10 represent the number of times that the response was given to the question. The most important thing that could be done to reduce helicopter costs, in the operator's opinion, is to eliminate or extend TBO (time between overhaul) intervals. Very closely related, the third most frequent answer was to improve reliability and maintainability (R&M). TBO's cannot be extended without improving R&M. A corollary question, number 8 shows by system where the operators feel that improvements should be made, and there are no surprises in that the rotor, engine and drive systems are enumerated. The responses to question 7 were too diverse to draw any conclusions, and question 7 along with 9 and 10 were added to the questionnaire for other purposes than cost analysis.

The results of the Boeing Vertol survey enable the operators' costs to be categorized to various levels so that the cost drivers can be identified. It was shown that operations and support (O&S) costs are almost double the acquisition cost of the aircraft, that direct support maintenance accounts for about 43% of the O&S costs, and that of the direct support maintenance costs, the split between parts and labor is about 50/50. Furthermore, the operators surveyed felt that elimination or extension of TBO's, the reduction of parts costs, and the improvement of R&M are the most important things that could be done to reduce costs. In the next section, the four elements that make up life cycle costs are defined, and discussions are given regarding their expected future behavior.

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3.0 LIFE CYCLE COST (LCC) ELEMENTS

Life cycle costs are the sum of research and development (R&D), production, operational and support costs. Table 3 shows the breakdown of life cycle costs into these categories for both Army helicopters and civil helicopters. The Army numbers are based on the reference 9 report, and the civil numbers are based on a weighted average of the commercial, corporate, and civil government responses to the Boeing Vertol Survey. The acquisition cost percentage of 32% for the commercial LCC breakdown has been subdivided into 5% R&D and 27% production, using the ratio of the Army R&D and production categories. This is predicated on the assumption that the price a helicopter manufacturer charges a commercial customer is based on the R&D and production costs which go into it, and that these would be in the same proportion for both military and commercial helicopter development and production. The operational category for the civil helicopters consists of the consumables, flight personnel, and insurance; the support category represents direct support maintenance. It is felt that the high percentage for support costs in the U.S. Army column, is due to the large number of personnel and facilities maintained by the Army to be prepared for wartime operation.

TABLE 3. LIFE CYCLE COST DISTRIBUTION

	U.S. Army	Civil
Research and Development	4%	5%
Production	21%	27%
Operational	19%	38%
Support	56%	30%

For purposes of this study, R&D costs include those funds necessary to design, develop, test and evaluate the aircraft. They also cover prototype tooling and manufacturing. Production costs consist of production engineering and tooling, manufacture of the aircraft and initial spares. Also included are the costs of changes to the aircraft. Operational costs as used here are comprised of the cost of fuel, oil and lubricants, and flight personnel. Support costs include the parts and labor necessary to maintain the aircraft.

3.1 R&D Costs

H. Reddick in his report "Army Helicopter Cost Drivers" (reference 9) gives a good treatment by category of what drives the cost of helicopters. Some of his major points are included here in the following sections. R&D costs in recent years have been affected and will continue to be affected by the emphasis on designing and testing for increased levels of reliability. Figure 6 conceptually depicts the relationship between R&D costs and O&S costs. Increased reliability is achieved through a growth process of test-analyze-fix, wherein through testing, failures and their causes are identified and design changes are made so that the failures do not occur in the future. As more testing is done, the cost of R&D increases. However, because failure modes are being eliminated, O&S costs are decreasing. Beyond a certain reliability level, it is no longer cost-effective to continue reliability testing because the cost of continued testing will not be sufficiently offset by reduced repairs. The top curve in Figure 6 is the sum of the bottom two curves. The optimum reliability level is indicated by the point where the sum of the two curves is at a minimum. Detailed discussions and examples of this concept can be found in references 10 and 11.

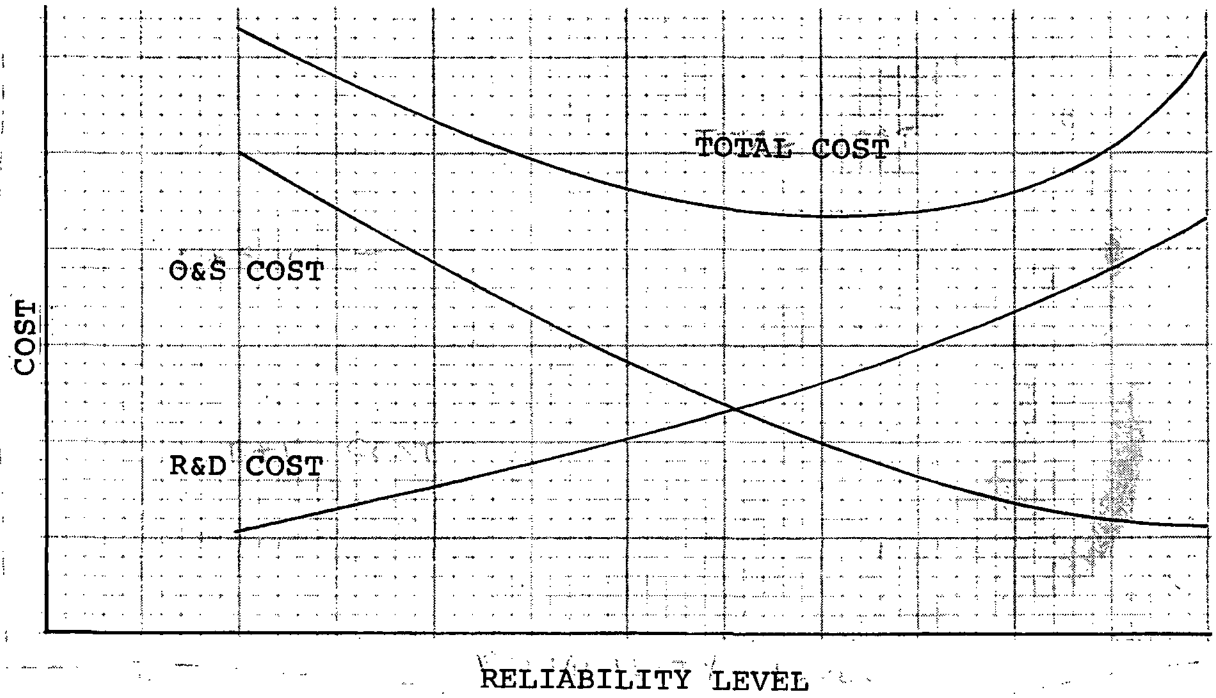


Figure 6. The relationship between R&D and O&S cost

3.2 Production Costs

Production cost can be divided into non-recurring costs such as tooling which is about 5% of the production cost and recurring costs which cover the actual manufacture of the aircraft. Table 4 shows a cost breakdown for a typical helicopter. The largest single contributor is the airframe itself and its costs of manufacture are directly affected by the number of parts, the fastener and rivet count, the rivet technique (hand or automatic), manufacturing techniques and number of manufacturing operations. The second largest cost contributor is the engine, and its cost generally increases with horsepower. The high cost components are the compressor which is dependent upon the type and number of stages, the turbine (and its number of stages), and the accessories, highest cost of which is the fuel control. Next on the list of production cost drivers is the rotor. The number 1 item in the rotor system is the blade itself, and its cost is driven by the number of operations required in its fabrication and assembly, plus the complexity of the airfoil shape. Also adding to blade cost are the deicing and crack detection systems. The cost of the second item in the rotor system, the hub, is also affected by the number of parts. Transmission production costs appear to be driven by the number of parts, tolerances, special processes, and in general by the complexity and critical nature of the transmission.

TABLE 4. HELICOPTER TYPICAL PRODUCTION (RECURRING) COST BREAKDOWN

Cost Contributor	Total Cost (%)
Airframe	25
Engine	20
Rotor	11
Transmission	9
	65
Other*	35
Total	100

*Avionics 10–20%

3.3 Operational Costs

Operational costs in the context of this report are composed of only two major items, flight personnel and consumables. In the U.S. Army LCC distribution, operational costs are split 60/40 between consumables and personnel, while in the civil distribution the split is about 54% for personnel, 29% for consumables, and 17% for insurance. Personnel costs consist of salary and training for flight crews. Consumable costs are dominated by fuel. The most significant parameter driving turbine engine fuel consumption is the compressor overall ratio. The higher the ratio, the better the fuel consumption for a given power level. The second but much less significant variable is turbine inlet temperature, again the higher the better. Naturally, insurance costs are determined by the accident rate.

3.4 Support Costs

The final cost category is that of support cost or direct support maintenance. It is comprised of the parts and labor used to maintain the aircraft. The average parts/labor split as reported in the Boeing Vertol Survey was about 50/50. Support costs are a direct function of first the reliability of the aircraft, that is, how often it fails or requires scheduled maintenance, and second the maintainability of the aircraft, this is, how long it takes to replace or repair a failed part, and how long it takes to perform scheduled maintenance. In the University of Virginia Survey, operators reported that 80% of all maintenance was scheduled and 20% was unscheduled. Scheduled maintenance includes periodic inspections of the aircraft and selected components, lubrication, greasing, and oil changes, and scheduled removal of major components for overhaul at specific time between overhaul (TBO) intervals. The largest contributor to the cost of scheduled maintenance is the scheduled overhaul of major components.

Although the unreliability of components tends to be associated exclusively with unscheduled maintenance or failures, it is the unreliability of parts which generates the requirement for scheduled overhauls. For example, if a certain set of gears or bearings is known to have a mean time between failure of 1,300 hours, the TBO interval for that transmission would be set at some value less than 1,300 hours to provide for the replacement of those gears or bearings *before they are expected to fail. Therefore, reliability impacts the frequency of both* scheduled and unscheduled maintenance. The cost is a function of the frequency of maintenance, the manhours and the cost of parts. Table 5 reproduced below from Research Requirements to Improve the Reliability of Civil Helicopters (reference 7), shows the reliability problems of civil helicopters by subsystem. This table was based on the review of over 1,500 Federal Aviation Agency Malfunction or Defect (FAA M or D) reports for turbine-powered civil helicopters for the years 1971 through 1976, and is pertinent primarily to unscheduled maintenance. Reference 7 also shows the top 20 individual reliability problems, the top 20 maintenance manhour problems, and the top 15 repair cost problems of civil helicopters. An appendix in that report provides a list and a detailed technical discussion of these problems. Figure 7 shows the top 15 problems which impact support cost. An asterisk has been placed next to those which contribute to low TBO intervals.

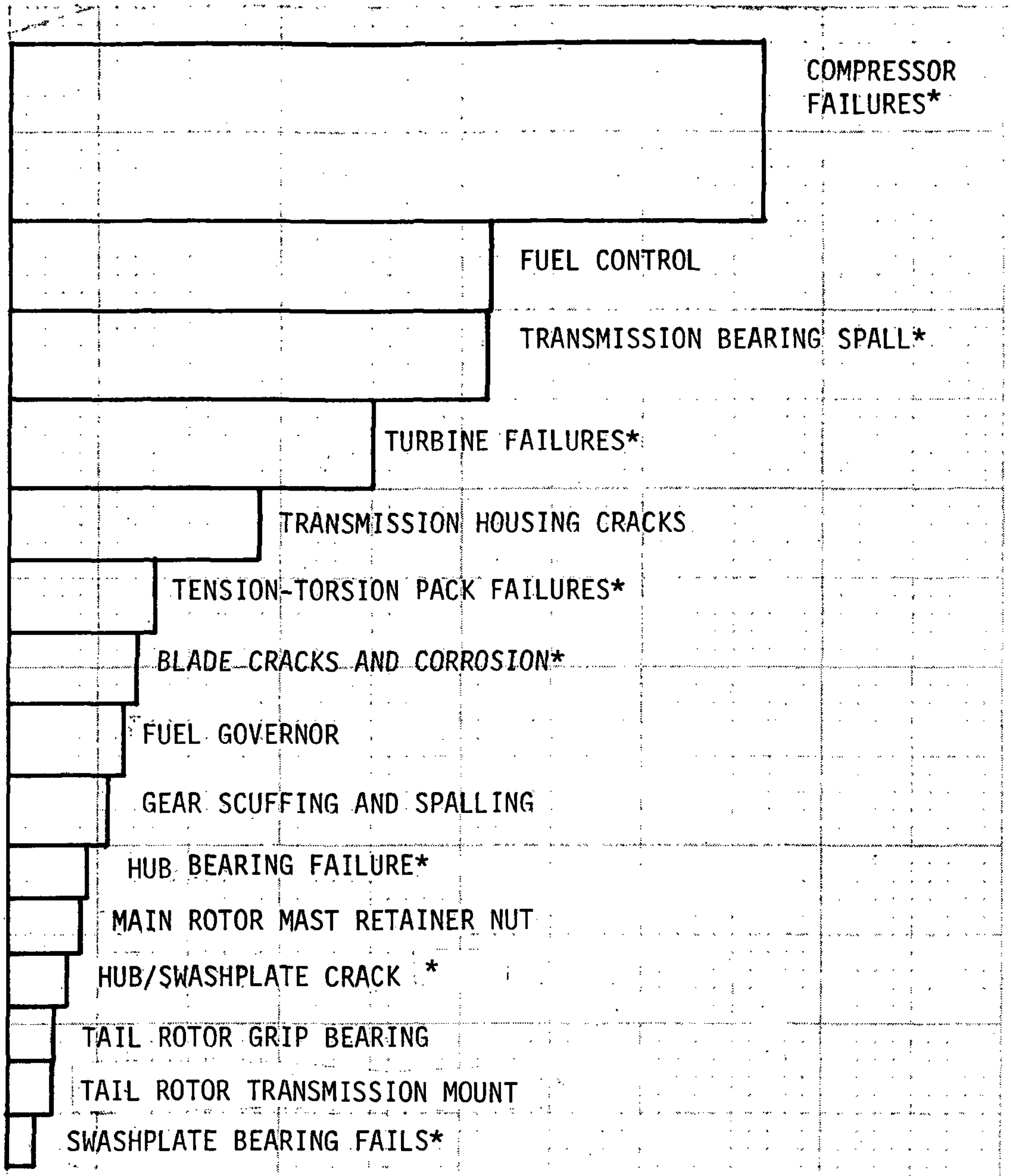
TABLE 5. RELIABILITY PROBLEM DISTRIBUTION BY SYSTEM

Subsystem	Relative Failure Rate (%)	Unscheduled Maintenance Manhours (%)	Repair Cost (%)
Propulsion (Turbine Power)+	35.3	25.1	66
Drive	13.9	35	21.3
Rotor	12.2	19.7	11.4
Airframe	19.9	10.1	1.2
Landing Gear (Floats)*	9.4	5.6	
Fuel	5	1.1	
Hydraulics	4.1	2.8	

\+ Only turbine-powered helicopters were included in this study.

* An aggressive reliability improvement program has virtually eliminated floats from the problem list subsequent to the data received for this study.

This section briefly described the four cost categories of life cycle cost and what factors affect each of the categories. Based on this discussion and what was learned from the operators through the two questionnaires, a more detailed distribution of life cycle costs was compiled in order to decide which problem areas should be worked in order to have the greatest LCC payoff. This distribution is shown in Table 6. A detailed rationale for the construction of this table is shown in the Appendix, but the primary goal was to break the cost contributors down to the lowest individual item level. Thus, flight personnel is the largest individual item because it cannot be further divided into any other categories.



*IMPACTS TBO INTERVAL

NOTE: AREA OF EACH PROBLEM BAR IS PROPORTIONAL TO PROBLEM MAGNITUDE.

SOURCE: REFERENCE 7

Figure 7. Top 15 problems impacting support cost

TABLE 6. DETAILED CIVIL HELICOPTER LCC DISTRIBUTION

	%	%	%
R&D	5	5.00	5.0000
Production	27		
Nonrecurring		1.35	1.3500
Recurring		25.65	
Airframe			6.4125
Engine			5.1300
Rotor			2.8215
Xmsn			2.3085
Avionics			3.8475
Other			5.1300
Operational	38		
Personnel		20.46	20.4600
Consumables		11.15	
Fuel			10.9300
Oil & Lube			.2200
Insurance		6.39	
Pilot			3.8596
Material			1.3100
Maintenance			.5048
Other			.7156
Support	30		
Engine		13.59	
Compressor			8.3400
Fuel Control			2.6786
Turbine			1.9753
Other			.5961
Drive		3.72	
Bearing Spalls			2.2575
Housing Cracks			.9161
Gear Scuff/Spall			.3599
Other			.1865

TABLE 6 – Continued

	%	%	%
Rotor		5.46	
T/T Assy.			2.3093
Blade Cracks/Corr.			1.0600
Hub Bearing			.4789
Other			1.6118
Airframe		1.68	1.6800
Misc.		5.55	5.5500
Totals	100	100.00	100.0000

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4.0 TECHNOLOGICAL DEFICIENCIES

In this section of the report, the technological deficiencies which contribute to the high costs of civil helicopters will be discussed. The problem is that today's civil helicopter fleet which forms the basis for the cost data previously shown, is a mix of aircraft of different age and technology level, ranging from the 1950's to the early 1970's. Some higher technology aircraft such as the Boeing Boelkow BO-105 and the Agusta 109 are not in the civil helicopter fleet in large numbers, while others such as the Aerospatiale 350C, the Sikorsky S-76, and the Bell 222 are not yet fully operational. Consequently, the data represents technological deficiencies which may not exist on today's generation of helicopters. Other problems may not be solved until the next generation of helicopters becomes available. This section will discuss the problems, what technology is available today, and what may be available in the future to reduce the life cycle cost of helicopters. The approach will be to discuss the problems in an order of priority resulting from Table 6 shown in the previous section. That table was organized by cost category. Table 7 below rearranges that data and shows the LCC distribution by percentage contributed by the top 20 items. However, before discussing each of these problems, some can be eliminated at this point. First of all, items 8 and 18 can be eliminated since no single significant item can be identified which would reduce these categories. In addition, it has been shown previously that an increase in R&D costs, and possibly production nonrecurring costs can be desirable if it will result in lower support costs, or lower acquisition costs in the case or production nonrecurring. Secondly, items 5, 7, and 17 represent miscellaneous categories, no single item of which could significantly reduce costs. The remaining 15 items which represent about 75% of civil helicopter LCC will be discussed below.

4.1 Flight Personnel

Based on the analyses conducted in this study, the largest single contributor to civil helicopter LCC is the cost of flight personnel at 20% of LCC. However, it is the problem for which there is no solution, nor perhaps is one required. In the Boeing Vertol Survey, when the operator was asked what could be done to reduce his helicopter costs, only twice in 36 questionnaires were people mentioned as a cost problem. Pilot salaries are not excessive. Based on the annual Professional Pilot magazine survey (reference 12), salaries ranged from an average low of $14,421 per year for an Enstrom F28 pilot, to an average high of $27,911 per year for a Sikorsky S-61 pilot. The average Hughes 500C pilot earns about as much as a trucker at $17,403, while the average Bell 206L pilot at $20,309 earns slightly less than a coal miner. At the present time there is an adequate number of helicopter pilots around, thanks to the Vietnam War. However it was reported in an earlier study (reference 13) that only about 300 pilots were to be trained by the combined military forces in 1976. During that year the number of civil helicopters operated in the U.S. and Canada increased by 959 (reference 14). As the civil helicopter fleet continues to grow there could be a shortage of pilots which would cause salaries to increase as demand increases.

The vast majority of the helicopters being operated today require only one pilot, so the high amount of flight personnel costs is not being caused by a requirement for two pilots. Two

TABLE 7. LCC IN ORDER OF CONTRIBUTION

		Past	Present	Future
1.	Flight Personnel	20.46	20.46	20.46
2.	Fuel Consumption	10.93	8.20	6.78
3.	Compressor Failures	8.34	6.59	5.92
4.	Aircraft Production Cost	6.41	4.49	3.46
5.	Miscellaneous Support Costs	5.55	5.55	2.78
6.	Engine Production Cost	5.13	4.62	3.85
7.	Miscellaneous Production Cost	5.13	5.13	5.13
8.	R&D Costs	5.00	5.00	5.00
9.	Pilot-Caused Accidents	3.86	1.31	.58
10.	Avionics Production Cost	3.85	3.85	3.85
11.	Rotor System Production Cost	2.82	2.54	.93
12.	Fuel Control Failures	2.31	0.00	0.00
13.	Transmission Production Cost	2.68	2.47	2.20
14.	Tension/Torsion Assembly Failures	2.31	1.93	1.55
15.	Bearing Spalls	1.98	1.79	1.60
16.	Turbine Failures	1.68	1.68	1.68
17.	Miscellaneous Airframe Failures	2.26	0.00	0.00
18.	Production Nonrecurring Costs	1.35	1.35	1.35
19.	Material-Caused Accidents	1.31	.45	.20
20.	Blade Cracks and Corrosion	1.06	.18	.06
	Other	5.56	5.56	2.78
	Total	100.00	83.15	70.16

pilot operation is dependent upon aircraft complexity and pilot workload. In fact, only a few aircraft such as the S-61, SA 321 and BV-107 have a two-pilot FAA minimum crew requirement. However, certain aircraft such as the SA 330 and the Bell 212, which are generally certificated for single pilot operation, do require two pilots for IFR flight. The only recommendation in this area, is that considering the trend toward IFR certification, the goal should be for single pilot IFR certification where possible. In summary, no decreases in flight personnel cost are visible in the foreseeable future.

4.2 Fuel Consumption

The cost of fuel as reported in the Boeing Vertol Survey, averages nearly 11% of total life cycle costs for helicopters. With the world energy resource situation such as it is, this topic takes on added significance since increasing fuel prices are inevitable. A considerable amount of research has been conducted in this area in association with NASA, and is thoroughly documented in references 15 through 18. The five technological areas which hold the promise of reduced helicopter energy consumption are specific fuel consumption (SFC) reduction, increased rotor figure of merit and cruise L/D_E, parasite-drag reduction, and reduced empty weight through the application of advanced-composite materials. Figure 8, reproduced from reference 4, summarizes the work that has been done to date and shows the percentage reduction in energy consumption possible for each technological feature. Figure 9, from reference 18, shows the development cost per unit of energy intensity saved by each technological area, and can be used to establish priorities. The figures show that fuel consumption can be reduced by 38.1% if research is completed in all technological areas except SFC reduction for conventional turboshaft engines. This can be separated to be about 18.5% from improved rotor efficiency, 11% from the regenerative engine, and 8.6% for reduced weight. A total R&D cost of $144 million has been identified in these reports as $16 million for rotor efficiency improvement, $55 million to reduce empty weight through advanced materials, and $73 million for development of a regenerative engine.

The 38% reduction in fuel is targeted as being achievable during the mid-1980's, but what can today's technology provide? In the reference 19 paper, it was stated that fuel costs of the Bell 222 can be expected to be 25% less than competitive models. It is assumed that competitive models refers to older technology aircraft of the same capability. Reference 20 shows similarly high fuel cost reductions for the AS 350, although exact amounts are not quantified. Independent calculations also show the Sikorsky S-76 to be in the same range as the Bell 222, so a 25% reduction will be assumed possible with existing technology.

4.3 Compressor Failures

The reference 7 report shows turbine engine compressor failures to be the number one reliability problem, from a cost standpoint, considering the failure rate, manhours, and parts cost. A discussion of the compressor reliability problem described in that report is repeated here.

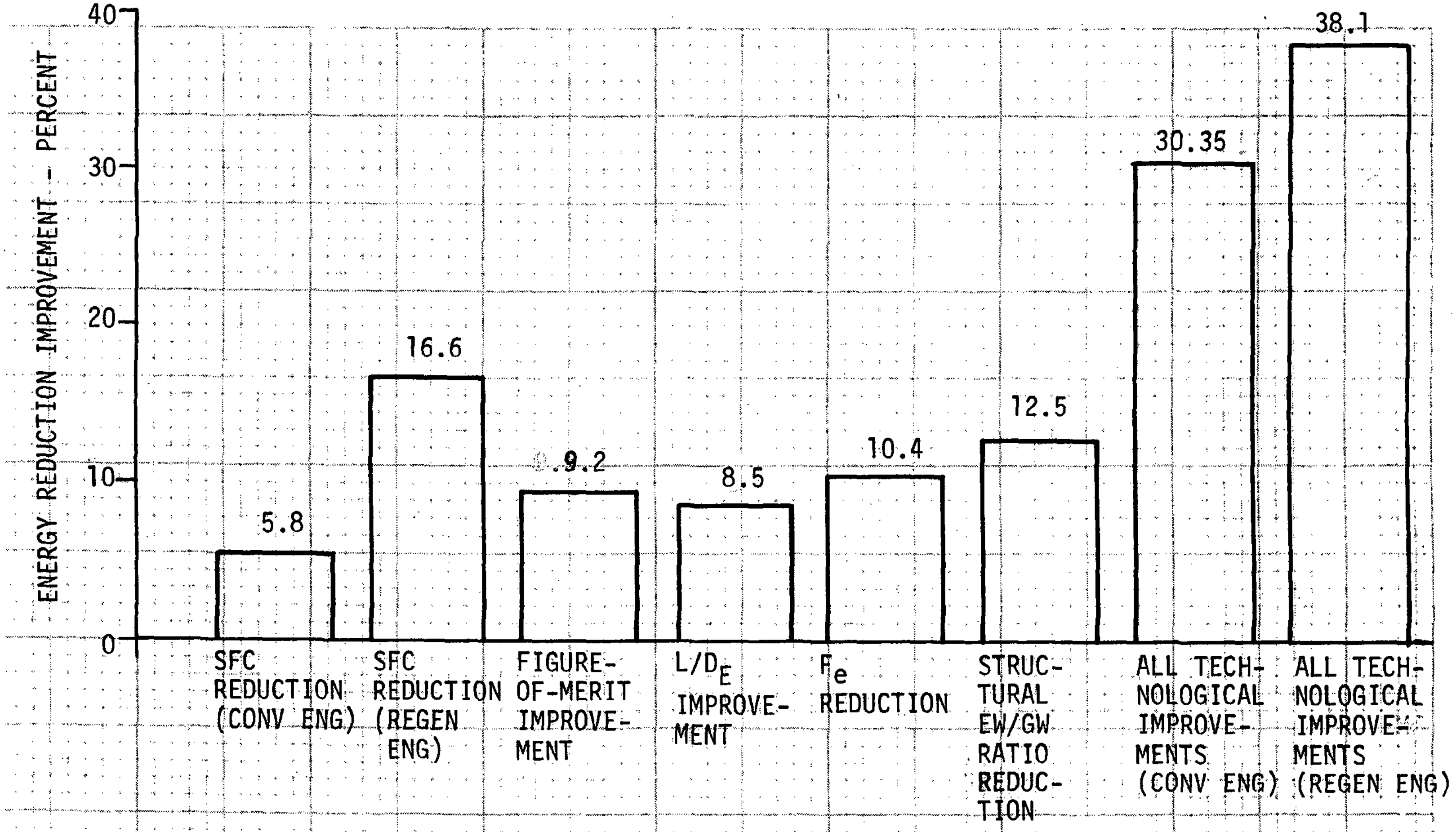

Figure 8. Advanced technology features for reducing fuel consumption

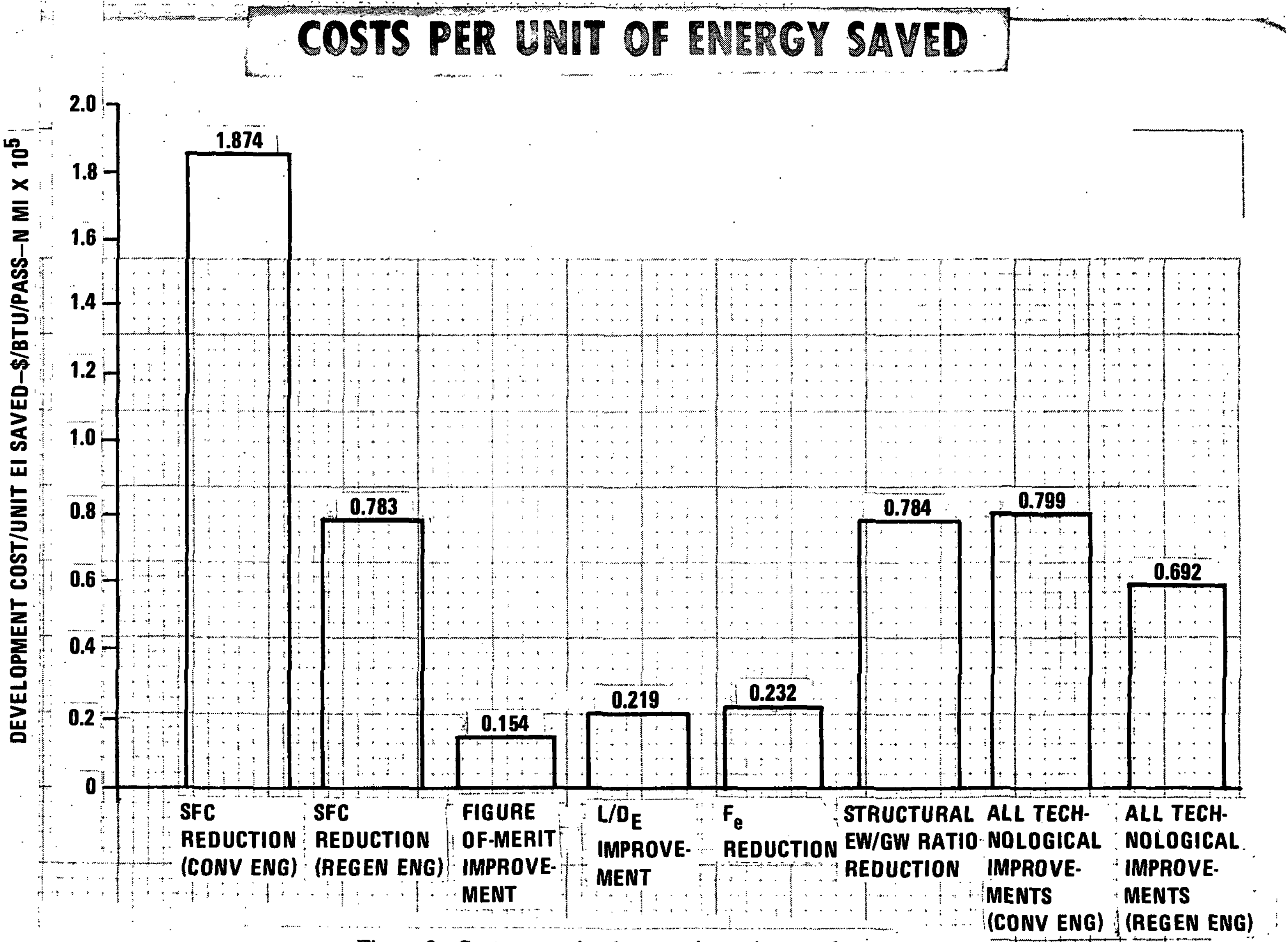

Figure 9. Costs per unit of energy intensity saved

Civil helicopter reliability data lists only "failure" as the principle malfunction of the compressor. Virtually every internal engine failure is cause for removal; therefore, to an operator failure description is of little importance. Also, the real failure causes and modes can usually be determined only after disassembly so they are not known to the operator.

A study of many of the same engines used in the civil fleet but installed in Army helicopters (ref. 21) reported the following as the major compressor failures modes: corrosion/ erosion-induced vane failures, blade/disk fatigue failures, diffuser cracking and leaking, compressor lining wear and cracking (unique to a particular engine), and variable stator and bleed problems.

The compressor failures must be examined in more detail to see if the civil helicopter problems are due to detail design execution or require an advancement in technology. The problems may be solvable with existing technology once the details of the failure modes are determined. It is possible that solution requires a means of establishing a cost incentive to justify the corrective action.

If, for example, FOD is the predominant cause of failure, the cost of the present poor reliability and engine repair may outweigh the adverse cost and weight of inlet screens.

It is recommended that a joint airframe/engine manufacturer effort determine causes and make recommendations for correcting compressor problems. To aid in this investigation, it is recommended that the FAA M or D report be revised to request that additional data on failure causes be supplied when this form is submitted by the engine overhaul facility.

Since the civil helicopter data base does not contain depot teardown/overhaul results, this discussion is based exclusively on military helicopter experience.

The development of erosion-resistant blade vane materials and corrosion-preventive coatings, coupled with the development/application of effective air particle separators, is required to reduce the magnitude of this problem. The GE T700 engine has addressed all of these problems and a study of the effectiveness of R&M improvements on the T700 is being conducted by GE for USAAMRDL. This may identify the areas of additional R&D testing, however, of 240 failure analysis reports filed on the YUH-61A (UTTAS) aircraft with the GE T700 engine, only 9 were related to the compressor, and 8 of these concerned compressor stalls.

In his reference 21 report, Rummel projects through normal reliability growth a 21% reduction in unscheduled engine removals due to compressor problems, and a 29% reduction if reliability and maintainability are emphasized during engine development. These two values will be used to project compressor cost reduction for the present and future.

4.4 Airframe Production Costs

Reference 9 states that basic helicopter airframe structure cost is comprised of about 11% for material, and 89% for manufacturing. Of the manufacturing costs, 30% is for fabrication and 70% is for assembly and installation. Marchinski, in his work (references 22, 23) showed that the manhours spent in manufacturing were a direct function of parts count or the number of parts in the subassembly. Another major contributor to manhours is the amount of hand riveting which takes place. The use of automatic riveting, wherever possible can reduce manhours by 75 to 80 percent. Low cost manufacturing techniques which can reduce costs include chem-milling, precision forging, and numerical control machining. Reference 23 showed that redesign of certain major assemblies of the CH-46F helicopter to consider lower parts count, a reduction in hand labor manufacturing and the use of lower cost manufacturing techniques, could result in a 44 percent manhour cost reduction. Another approach which reduces parts count and manufacturing processes, is the use of composite material for structure instead of the traditional skin/stringer technique. Reference 24 shows that about 7% of the airframe structure of the CH-53D was made of fiberglass epoxy. The study showed that the all-molded fiberglass/epoxy cockpit canopy costs about 64% less than traditional airframe structure. The Sikorsky S-76 cockpit canopy is a direct descendant of the CH-53D canopy, and consists of 3 premolded fiberglass parts. The S-76 uses composites extensively, including Kevlar-49/epoxy, fiberglass epoxy and graphite epoxy. Another example of progress being made in the area of airframe structure is found in the reference 20 paper, which states that structure parts count for the AS 350 is at 300, compared with 1,000 for the Alouette II. This is partly accomplished through the use of molded cowlings of fiberglass resin laminates and a canopy made of thermoformed polycarbonate panels. The only drawback to the use of composites is that their material cost can be higher than metal.

Estimates of the total acquisition cost savings achievable in the airframe structure area vary widely. An approximation of what can be achieved with today's technology is a cost reduction of 30%, with a saving of 46% projected for the future. This is based on a recent presentation by Boeing to NASA, identifying rotorcraft research areas.

4.5 Engine Production Cost

Turbine engine acquisition cost represents about 5% of the total LCC of the helicopter. According to the reference 25 report, this cost is nearly evenly divided among the turbine, compressor, and accessories at 29.3, 31.2 and 32.9 percent, respectively. The remaining 6.6% is accounted for by the combustor. This report presented seven areas for acquisition cost reduction, the most significant being manufacturing methods, advanced materials, parts reduction, and advanced concepts for controls and accessories. In the area of manufacturing, the report recommended improved casting techniques to allow casting of static parts which are usually forged or machined, and integration of one or more parts in a single casting or forging. Improved material utilization could also reduce costs, since it currently takes 5 pounds of raw material to make 1 pound of finished product in many cases. Powder metallurgy offers some promise in this area. With regard to materials, ceramic materials are under consideration since they can operate under high temperature conditions, and can reduce costs due to the elimination of the requirement to fabricate turbine cooling passages. In reference 25, Balliett foresees a 10% reduction in acquisition cost attainable with today's technology, and a 25% decrease possible in the mid-1980's.

4.6 Pilot-Caused Accidents

What we are really talking about is insurance, the cost of which is a direct function of the accident rate. In his report on the safety of civil helicopters (reference 1), Ken Waters shows that about 60% of helicopter accidents can be attributed to the pilot, based on an analysis of 293 accidents which occurred in 1975. The top five reasons for pilot caused accidents were failure to maintain adequate rotor RPM, misjudgement of speed or altitude, improper operation of flight controls, inadequate preflight planning, and failure to see or avoid obstructions. Four recommendations are made to reduce the number of accidents caused by pilots:

1. Improve pilot training, qualifications, and professionalism.
2. Improve flight operational planning and directives.
3. Design changes to make the helicopter more tolerant to hazardous environments through improved stability and control.
4. Provide the pilot with an advanced systems monitor to reduce workload.

The civil helicopter accident rate for 1975 was 18.93 per 100,000 flight hours. The U.S. Army rate has leveled at about 6.48 per 100,000 flight hours. For the purposes of this report, the percentage reduction from 18.93 to 6.48 (66%) will be considered to be the percentage improvement possible with today's technology. The U.S. Army goal for the future, to be demonstrated by the UTTAS aircraft is 3 accidents per 100,000 flight hours. The percentage reduction from 18.93 to 3 (85%) will be considered to be the percentage improvement achievable in the future.

4.7 Avionics Production Cost

The costs of avionics packages can vary widely, since the quantity and type of equipment purchased depends on the operator's needs and preferences. A typical basic package may include a transceiver, a VOR system, an ADF and a transponder. On the other hand, a complete avionics system supporting IFR operation, can increase the cost of the helicopter by 25 percent or more above the base price. As with a lot of electronic equipment, price reductions over time are common for certain items, and other items progress to increased capability without increased cost. However, inflation eventually tempers many of these price reductions. The trend in avionics is away from individual, quickly replaceable cockpit panel units, and toward integrated multi-function packages. This trend will result in lighter weight avionics systems, but does not portend any price decreases. In summation, while discrete price reductions may be seen sporadically, and individual operators may lower their particular costs, the trend towards IFR and avionics integration will not result in lower cost, so the avionics contribution to LCC will not change.

4.8 Rotor System Production Cost

Some of the most dramatic technological changes in recent years have been made in the rotor system. The most publicized development has been the introduction of composite rotor blades. Composite blades have been in production for years on the Boelkow BO-105 and certain Aerospatiale machines, and will be seen in varying use on some of the new aircraft such as the Bell 222 and Sikorsky S-76. U.S. composite blade manufacturers include Boeing, Kaman, Bell and Sikorsky. The main cost benefits of composite blades are found in reduced maintenance cost, however, it is believed that reduced production costs can be achieved although little quantitative data has been published in this area. The reference 20 report states that through a new automatic manufacturing process, the blades for the AS 350 can be produced at a third of the cost of the blades for the SA 341. Tail rotor developments include the use of composites, self-lubricating bearings or bearingless hubs. Main rotor hub developments consist of the use of elastomeric bearings and semi-rigid and hingeless rotor systems typified by the BO-105 and AS 350 designs. The AS 350 hub parts count was reduced from 377 components to 70, with a 45% reduction in weight. Reference 26 reports a 75% cost savings for this hub, but again little or no additional published data was found which quantified the cost savings found in other new main rotor hub and tail rotor designs. Consequently, the 67% blade cost reduction reported by Aerospatiale for its AS 350 glass blades will be used as the goal for the future, while a more conservative 10% reduction in cost will be used as an estimate of what is achievable today. (In its OH-58 composite blade program, the U.S. Army is using a 10% cost reduction as its goal.)

4.9 Fuel Control Problems

The reference 7 report gives a good description of the problems associated with fuel controls, and is repeated here.

The turbine engines widely used in civil helicopters have a gas generator-turbine-compressor unit and a power turbine. The fuel control portion of the fuel system provides the fuel management during engine starting and up to the flight range of the power turbine, approximately 85 to 100 percent of the normal flight rpm. In the upper speed range, the governor controls the speed. Common malfunctions of the fuel control are improper starting and fluctuations of speed in the lower ranges. There is little corrective action possible for fuel controls in the field, so the most common correction of a malfunctioning fuel control is to remove and replace the unit. Often a unit is removed as part of a troubleshooting operation and subsequent test and disassembly show the unit is fully functional with no defect.

A study of the turbine engine reliability problems of Army helicopters (reference 21) reports the following failure modes of fuel control units. Contamination occurs from the actuating media or from the fuel itself causing sticking and binding of spools, leakage of valves, and clogged orifices. Wear is found on moving or contacting elements. Springs, bellows, and retention devices fail due to fatigue, with the remaining problems due to misadjustment, erroneous troubleshooting, etc. (estimates of this problem are as high as 50%).

The problems are not defined in detail in the civil helicopter data base. The prime engine manufacturer does not usually perform the detailed design, manufacture, or overhaul of the fuel control and seldom has detailed awareness of failure mode and frequency of this assembly. The area needs considerable study to define the problem prior to establishing a solution. Records do indicate substantial differences between failure rates on the fuel controls of different model helicopters, indicating some technology is present for alleviating the problem.

A fleet evaluation program of the comparative reliability of present engine fuel controls with similar units protected by better filtration is recommended. This will document the magnitude of the possible reliability improvement and cost, weight, and complexity penalties of improved filtration. It is also recommended that a joint airframe/engine/control manufacturer effort determine causes and make recommendations for correcting fuel control problems.

This item is one of the major erroneous-removal problems encountered in turbine helicopters. As many as 65 percent of the military helicopter fuel controls removed in the field exhibit no defect when tested in the shop. This problem appears to be installation/interface-related and is a candidate for additional research prior to complete problem resolution.

A field diagnostic/inspection technique is required so that erroneous removals can be minimized. One option to be considered is the development of a field-level GSE item for off-aircraft fuel control checkout.

The reference 21 report projects through normal reliability growth an 8% reduction in the unscheduled engine removal rate due to fuel problems, and an 18% reduction if reliability and maintainability are emphasized during development. These two values will be used to project fuel control cost reductions for the present and future.

4.10 Transmission Production Cost

The reference 27 report showed that of the hundreds of parts that make up a helicopter transmission, 7 of these components account for 63% of the production cost, and 23 parts account for 75% of the cost. In order to realize a significant saving in production costs, these major components must have high priority in the design process. An advanced transmission design which is described in that report includes such changes as elimination of the shaft portion of the rotor shaft, integration of housing and upper cover into one unit, integral bearing races with gear shafts, and general simplification of the assembly as a direct result of the new arrangement. Although this design was optimized for low maintenance cost, the changes are estimated to provide a 20 percent reduction in the production cost of the assembly. (A contract recently awarded for advanced transmission design by the U.S. Army Applied Technology Laboratory at Ft. Eustis also has a 20% recurring cost reduction as its goal.)

The reference 28 report describes the main transmission in the Sikorsky S-76, which has as its final reduction a bull gear with two spur gear inputs instead of a typical planetary system. Using the simplified system reduces the number of bearings and gears by a significant amount, and projects a 30% decrease in production cost. Reference 20 describes the main transmission in the Aerospatiale AS 350 as a "very simple design with one stage of epicyclic gears and a couple of bevel gears." It also states that the parts count and production cost have been reduced by about 50%.

The calculated average of these 3 estimates of transmission production cost reduction is 33%, and will be used as an estimate of what can be attained in the future, while half that amount (16.5%) will be used as an estimate of what cost reduction could be achieved with today's technology.

4.11 Tension-Torsion Assembly Failures

The reference 7 report showed tension-torsion assembly failures to be a significant contributor to cost, based on an analysis of FAA M or D reports, and considering manhours to repair and parts cost. A discussion of the problem contained in the report is paraphrased here.

> The tension-torsion assembly retains the blade against centrifugal forces while permitting the torsional movement required for blade control. Catastrophic blade loss has resulted from wirepack tension-torsion assembly failures in current turbine helicopters. As the function of the pack assembly is critical to safe operation and any pack deterioration cannot be observed in the aircraft installation, the packs are replaced when any deterioration is found at overhaul, regardless of how serious.
>
> Two forms of deterioration have been observed; first, the polyurethane cover deteriorates from hydraulic, oil, or other fluid contamination. This becomes evident from the blistered appearance. (Cover deterioration is a possible cause of pack failure.) Second, broken wires protrude through the cover. Although the pack consists of multiple wire windings, the assembly shows little sign of redundancy and acts as a single load path for blade retention.
>
> It is probable that continued effort will soon result in complete understanding of problem causal factors and solutions of the wirepack problems. Other approaches for the blade retention problem which have been successfully used are the following:
>
> 1. A series of angular-contact ball bearings sharing the centrifugal load as a thrust load on each bearing.
> 2. Many parallel stainless-steel straps carrying the centrifugal load as a shared tension load and twisting to provide blade pitch freedom.
> 3. Many parallel metal bars carrying the centrifugal load as a shared tension load and twisting to provide blade pitch freedom.
> 4. Elastomeric bearings in compression.

These approaches are in use, and as far as is known, none has resulted in a safety-of-flight problem. Some offer positive redundancy in load path and better inspectability of condition. Some require a configuration change to the rotor head. Weight and cost may be slightly affected adversely.

Bearingless rotor hubs with a torsionally flexible composite element to retain the blade are under development and offer promise of weight and cost savings and reliability and maintainability improvement. Continued development of bearingless composite hubs is recommended.

The magnitude of this problem is a result of the use of a specific method of blade centrifugal retention, and other design approaches for blade retention have virtually eliminated the problem.

4.12 Transmission Bearing Spalling

The discussion of this problem from the reference 7 report follows:

Spalling (or flaking) of bearing is the result of fatigue failure of the contacting surfaces. If the bearing is properly made, mounted, and lubricated and the loads are not excessive, bearing spalling should occur only infrequently.

Common problems found to contribute to transmission bearing spalling are the following:

1. Unanticipated loads, in excess of the design load spectrum.
2. Lack of cleanliness of the bearing material. Inclusions or flaws act as origins for incipient failure.
3. Misalignment or other assembly conditions such as to cause an unanticipated distribution of load.
4. Improper surface finish of the ball, roller, or raceway paths such that lubrication breakdown occurs.
5. Contamination of the lubricant.

In the civil helicopter data base, this problem is associated predominantly with the spalling of the upper shaft support bearing in one model of helicopter and, as such, is not a generic problem to the civil helicopter of the magnitude indicated but rather a particular problem in design execution. Although the magnitude of this problem may be biased by this one specific bearing, bearing spalls are the cause of more than 19 percent of all military helicopter transmission unscheduled removals.

The particular problem in the one helicopter model that drove this failure cause to the predominant problem list appears to be a matter of design execution. Correction is probably impaired by cost and weight changes and the necessity to change interfacing components.

The generic problem of transmission drive system bearing spalling can be alleviated within the bounds of present bearing technology. Incorporation of the following product improvement-type design approaches will reduce the problem magnitude:

1. Bearings of VIM-VAR processed steel (M50 or 9310, vacuum-induction-melted or vacuum-arc-remelted) with the forged billet ultrasonically inspected. This material gives fewer and smaller inclusions for possible fatigue failure initiation than single vacuum-arc-melted steels with conventional inspection techniques.

2. Improved quality assurance of critical bearing characteristics such as surface finish and internal clearances, assuring better lubrication and more predictable load-carrying ability.

3. Since spalling is a load-sensitive characteristic, increasing the size of the bearing will reduce the surface contact stresses. The bearing life increases as the inverse of the 7th or 9th power of the contact stress ratios if all other factors remain unchanged. This approach does carry a weight penalty but, since total weight of transmission bearings is about 7 percent of the transmission assembly weight (ref. 27, Figure 18), a trade of this sort (weight increase to increase reliability)may be in order. The problem could then be seen in proper perspective.

The following approaches in the area of advanced technology may further reduce the transmission bearing spalling problem:

1. The civil helicopter fleet has more freedom to use lubricants more suited to the specific application than does the military, which relies on a universal lubricant, suitable for all applications and environments (but possibly optimum for none). Research shows that for many helicopter applications, straight mineral oil gives about twice the life of the military lubricants. One concern is that introducing more lubricant types could create additional logistics (supply) problems.

2. Continued materials research to develop stiffer transmission housings and bearing materials with better load-carrying characteristics.

3. Vibration reduction to reduce unanticipated loads upon the bearings.

4.13 Turbine Failures

Reference 7 describes the problems associated with the power turbine section of turbine engines.

> Civil helicopter reliability data lists "failure" as the principle R&M impacting malfunction of the engine. Virtually every internal engine failure is cause for removal, so to an operator failure description is of little importance. The real failure causes and modes can usually be determined only after disassembly, so they are not known to the operator.
>
> A study of Army turbine engines made to determine R&M factors (reference 21) covered many of the same engines used in the civil helicopter fleet. This report gave the following as major turbine failures modes: nozzle band cracking, nozzle support structure wear/cracking, nozzle erosion, burning and sulfidation. Blade/wheel cracking is an infrequent failure mode. This area is safety-impacting and is given a proportionally larger amount of design attention. The major R&M problem, then, is caused by thermal stresses, thermal weakening, and the erosive effects of the hot gases.
>
> The civil helicopter turbine failure data base should be expanded to allow examination in greater detail. While some problems appear to be alleviated by existing design techniques, the inevitable use of higher turbine pressure ratios and operating temperatures and the trend to increase power-to-weight ratios make this an area for continued research. A joint airframe/engine manufacturer effort is recommended to determine causes and resolution of turbine reliability problems.
>
> Since the civil helicopter data base does not contain depot teardown/overhaul results, the discussion below is based exclusively on military helicopter experience. The use of cast nozzles and slotted inner/outer nozzle bands, along with the development and application of improved materials, directional solified alloys, and improved coatings to resist sulfidation, would be a great step toward reducing the magnitude of this problem. Analogously, development/application of turbine engine fuels with lower sulphur content would have a highly beneficial effect upon turbine reliability. A materials/coating development program is recommended to alleviate future turbine area problems.

The reference 21 report projects through normal reliability growth a 19% reduction in the unscheduled engine removal rate due to turbine problems, and the same reduction even if R&M were emphasized during development. For purposes of this report, a 19% cost reduction will be assumed for future engines, with half that amount (9.5%) achievable with today's technology.

4.14 Material-Caused Accidents

This problem directly affects the helicopter operator's insurance costs. The reference 1 report attributed to material, 20.5% of 293 helicopter accidents which occurred in 1975. The primary factors were fatigue fracture, material failure and a lack of quality control at the time of manufacture or overhaul. No new technology is foreseeable at this time to reduce this type of accident, however, research to identify the prime factors in material-caused accidents is necessary. As with pilot-caused accidents (par. 4.6), there is no reason to expect that civil operators cannot achieve the lower accident rates exhibited by the military, so for purposes of this study the projected reduction in material-caused accident rates will be the same as for pilot-caused. A 66% reduction is considered possible with today's technology, and an 85% reduction should be the goal for the future.

4.15 Metal Blade Cracking and Corrosion

The problems of metal blades are well known and documented, and may soon become history with the advent of composite blade technology. Reference 7 gives a brief discussion which is repeated here.

> The metal blade consists of an aluminum extruded spar with an aluminum sheet-metal fairing bonded to the trailing edge. Common failure modes are cracking (predominantly in the bond areas) and corrosion. These are not safety-of-flight problems but must be corrected before they progress to that stage. This blade concept, while initially inexpensive, is very difficult to repair and so a large proportion of damaged blades are scrapped. The blade is susceptible to FOD. Repair of dents makes the blade susceptible to further cracking of the dented area, resulting in subsequent scrapping.
>
> The fiberglass composite blade is much less susceptible to bonding cracks, denting, FOD, or corrosion. Although the initial cost of this blade is presently high, with increased production quantities the initial costs are projected to be similar to metal blades. Repair has been simple and inexpensive, resulting in low life-cycle costs.
>
> The use of advanced composites gives better weight-to-strength ratios with R&M characteristics similar to fiberglass and offers overall helicopter performance gains. Thus, the value of advanced composite material application to blades will be in the area of providing R&M characteristics comparable to fiberglass, while simultaneously providing a weight/performance improvement which can be applied for reliability improvement elsewhere in the helicopter.

An analysis performed in-house at Boeing shows a potential blade operating cost reduction on the order of 83% for the U.S. Navy H-46 aircraft with fiberglass blades. A similar analysis performed in support of an Army contract to design an OH-58 composite blade, showed a potential blade operating cost reduction of 95%. These two values will be used as the range of achievable improvement with present and future technology. The reference 29 report which discusses the composite rotor system experience of the BO-105 after one million blade hours, calculates a fatigue life of 22,000 hours for that blade.

4.16 Summary

Based on the discussions contained in this section, Table 7 has been augmented to illustrate the LCC reductions which are possible with today's technology and technology of the future. This is shown in Table 8. The first column shows the total life cycle cost normalized to 100, and the cost drivers for civil helicopter operators. The second and third columns were calculated based on the percentage cost reductions which were explained in this section. The present technology column is based primarily though not exclusively on what may be seen in the latest generation of aircraft (e.g., S-76, B-222, AS 350), while the future column will not be achievable without additional research. (Some research may still be necessary to demonstrate some of the cost reductions expected in the present technology column.)

Finally, some of the technological improvements in one area have a carryover effect into another area. For example, the rotor efficiency research to reduce fuel consumption also projects a 6.75% reduction in operating cost. To account for these compound benefits, the final category in Table 7 – "others", and the miscellaneous support costs have been reduced by 50%.

Figure 10 illustrates these projections graphically.

TABLE 8. CIVIL HELICOPTER LCC IMPROVEMENT

	Past	Present	Future
Flight Personnel	20.46	20.46	20.46
Fuel Consumption	10.93	8.20	6.78
Compressor Failures	8.34	6.59	5.92
Airframe Production Cost	6.41	4.49	3.46
Miscellaneous Support Costs	5.55	5.55	2.78
Engine Production Cost	5.13	4.62	3.85
Miscellaneous Production Costs	5.13	5.13	5.13
R&D Costs	5.00	5.00	5.00
Pilot – Caused Accidents	3.86	1.31	.58
Avionics Production Cost	3.85	3.85	3.85
Rotor System Production Cost	2.82	2.54	.93
Torsion Tension Assy. Failures	2.31	0.00	0.00
Fuel Control Problems	2.68	2.47	2.20
Transmission Production Cost	2.31	1.93	1.55
Turbine Failures	1.98	1.79	1.60
Miscellaneous Airframe Failures	1.68	1.68	1.68
Transmission Bearing Spalling	2.26	0.00	0.00
Nonrecurring Production Costs	1.35	1.35	1.35
Material – Caused Accidents	1.31	.45	.20
Metal Blade Cracking & Corrosion	1.06	.18	.06
Others	5.56	5.56	2.78
Total	100.00	83.15	70.16
% Reduction		16.85	29.84

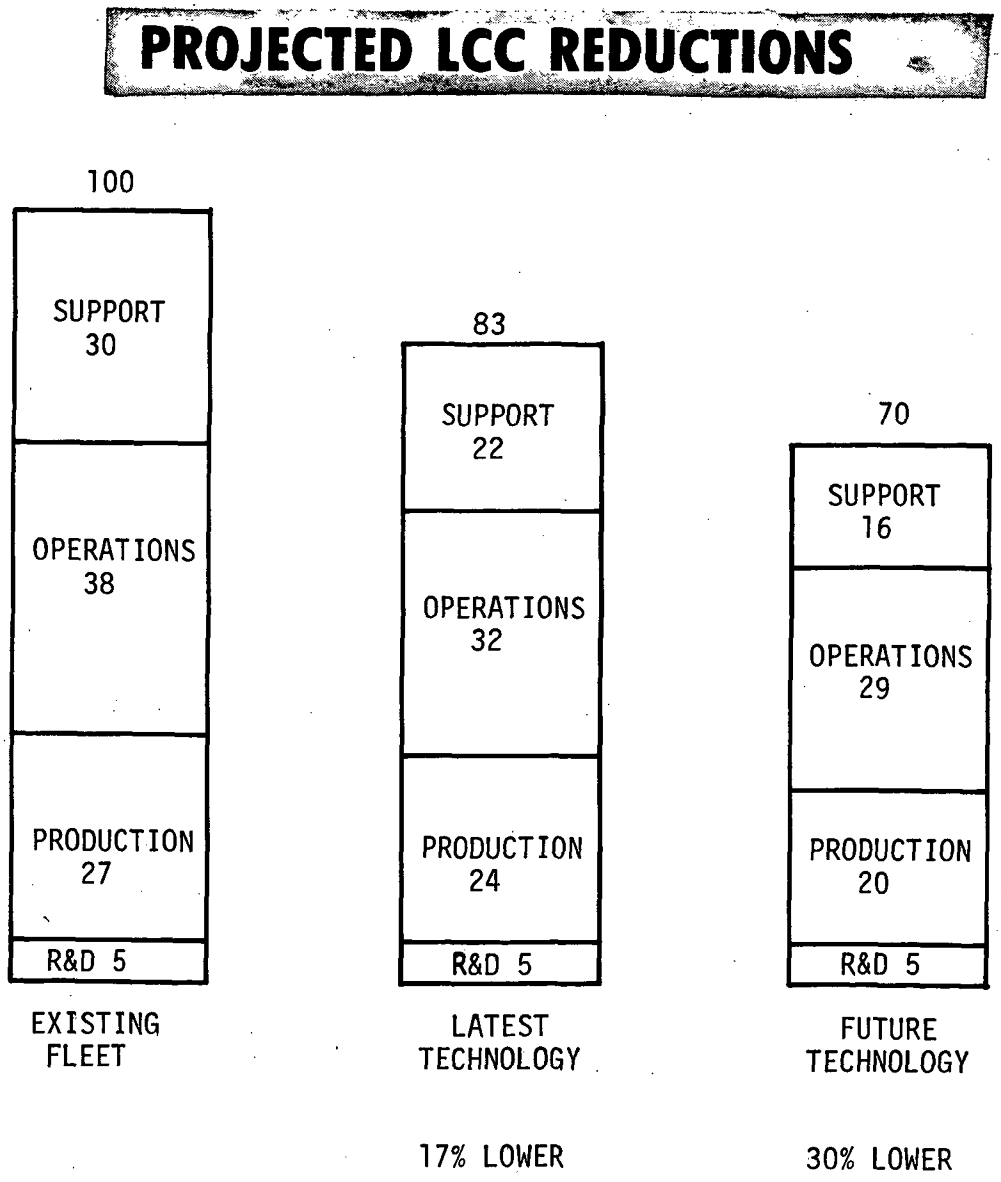

Figure 10. Projected LCC reductions

5.0 MANAGEMENT DEFICIENCIES

Although little attention was given to management deficiencies in this study, a few comments are in order. One of the most frequent complaints of the helicopter operators had to do with the regulatory environment surrounding helicopter operation, that is the FAA (see question 10 in the Boeing Survey). The biggest complaint was that the FAA had difficulty viewing the helicopter as different from fixed-wing aircraft. While it is common for those who are regulated to complain about the regulators, one example may illustrate the problem. In reference 2 it was stated that although the current fleet of 7,000 civil helicopters accounts for less than 4% of all civil aircraft, over 20% of all FAA Airworthiness Directives were directed at the civil helicopter fleet (see also response 5 to question 6 in the Boeing Survey). This seems to be penalizing helicopter operators disproportionately.

Regarding the manufacturers, many operator criticisms concerned manufacturer disinterest both in designing the helicopters and in service after the sale. Some operators felt that commercial helicopters were nothing more than warmed-over military designs. Perhaps the newer helicopter breeds will help to dampen this criticism. Operators also complain about parts costs and availability, and reduction of component service lives, and the trend toward component warranties will help to alleviate these problems.

On the other hand, perhaps the operators expect a little too much in certain areas. Some expect parts and service policies to be equal to the well-established automobile service organizations, and parts prices to be similar. A recent article in Professional Pilot Magazine (reference 30) cited excessive price increases for helicopter parts between 1974 and 1977. In fact some of the price increases were high, but the calculated average increase was 35.6%, which is lower than the DoD price index of 36.3% for commerce and industry purchases for the same period.

Due to the wide variety of TBO (time between overhaul) intervals in existence for the current civil helicopter fleet, it was not possible in this study to estimate the contribution to LCC of scheduled overhaul of major dynamic components. However, elimination or extension of TBO intervals was the most frequently used response by the operators to the question of how costs could be reduced, when asked in the Boeing Survey. A discussion of this problem is contained in reference 6. Methods of establishing TBO's vary and are not always consistent nor rigorous. The only good reason for a scheduled overhaul, is to prevent the failure rate from increasing, or for reasons of flight safety. From a cost standpoint it is almost always more cost-effective to be "on-condition" than to have a TBO. Reference 31 contains a discussion of the on-condition maintenance concept as it applies to transmissions, and the principles are equally applicable to other components as well. Some of the R&M-oriented research identified in this study will also permit the extension of TBO intervals and service lives, but the exact cost impact has not been calculated.

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6.0 RESEARCH REQUIREMENTS

This section describes seven research programs required over the next 5 to 7 years to achieve the reduced helicopter life cycle costs described in Section 4.0

6.1 Reduced Fuel Consumption Research
$144 Million 7 Years

The research required to achieve a 38% reduction in fuel consumption as described in reference 4, consists of three programs, improved rotor efficiency ($16 million), development of a regenerative engine ($73 million), and reduction of aircraft empty weight ($55 million). These research programs are described in detail in references 18, 16 and 17, respectively. In terms of payoff the rotor efficiency research offers the best return on investment.

6.2 Engine R&M Research
$100,000 1 Year

The three contributors to engine operating cost are the compressor, turbine and fuel control. For purposes of R&D, the three problems should be combined into one study which would define the most cost-effective methods of reducing failures of these three items in helicopters, and structure a research and development program to design test and qualify an R&M-improved turbine engine. Full details should be defined by an engine manufacturer.

6.3 Airframe Production Cost Research
$2 Million 5 Years

This program would have to be reconciled with the reduction of empty weight research, to assure that the programs complement each other. Since raw materials for composite structure are more expensive than for metal structure, the purpose of this research would be to seek ways of reducing material cost, and to advance the composite design and fabrication techniques required to maximize the advantages of reinforced composites. The result would be the design, construction and testing of composite structural modules.

6.4 Engine Production Cost Research
$3 Million 5 Years

Research to reduce the acquisition cost of turbine engines would consist of the refinement of manufacturing techniques to use construction materials more efficiently, also considering new technology such as powder metallurgy. Advanced engine materials such as ceramics should be developed, parts count should be lowered, and advanced concepts for controls and accessories should be considered. Full details of such research should be defined by an engine manufacturer.

6.5 Safety Research
$7.6 Million 4 Years

In order to reduce helicopter operator insurance costs, research in the area of safety is required. A complete helicopter safety R&D program is defined in the reference 1 report. The only additional recommendation here is that the program be implemented over 4 or 5 years, and that more of the funding be redirected toward solving the problem of pilot-caused accidents.

6.6 Rotor Production Cost Research
$2 Million 3 Years

The maintenance costs of composite rotor blades are significantly lower than the costs of metal blades. The next step is to ensure that composite blades can be produced more economically than metal blades. Part of this research program would be to refine composite blade manufacturing techniques and to examine the possibility of reducing material costs. Secondly, bearingless main rotors such as the one under development at the Boeing Vertol Company, have been designed and project lower acquisition costs than conventional rotor systems. The rest of the research in this program would be for production cost verification, through the optimization of tooling and manufacturing techniques required to produce bearingless main rotors.

6.7 Transmission Research
$9 Million 7 Years

The problems of helicopter transmission production cost and bearing spalling which were discussed in Section 4.0 would be addressed in an integrated program to develop an advanced technology helicopter transmission. Although other drive system problems such as housing and mount cracks, gear scuffing and spalling were not identified as major LCC contributors, others will argue that their costs are significant, and these problems would also be addressed in this research program. Reference 27 describes a complete research program to develop an advanced technology transmission at a cost of $10 million, however, work sponsored by the U.S. Army Applied Technology Lab is already going on at Boeing Vertol to begin development at nearly $1 million so the cost of the recommended program has been reduced to $9 million.

6.8 Size, Configuration, Mission Applicability

Except for the engine-oriented research which applies only to turbine engines, the research described above has general applicability to helicopters of all sizes, configurations and mission types.

7.0 CONCLUDING REMARKS

This study identified the major life cycle cost drivers for civil helicopter operators. The three largest cost contributors were flight personnel, fuel, and engine maintenance. Based on technology currently available in the latest generation of helicopters, it was estimated that life cycle costs would decrease by about 17%. Considering advanced technology, it was projected that helicopter life cycle costs could be reduced by about 30%. The following research areas were identified to achieve this reduction:

- Reduced Fuel Consumption
- Turbine Engine R&M
- Airframe Production Cost
- Engine Production Cost
- Safety
- Rotor System Production Cost
- Advanced Transmission

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APPENDIX

The purpose of this appendix is to provide the rationale behind the development of table 6 in Section 3.

The first step was to combine the civil government and commercial operator distributions shown in the responses to questions 3 and 4 on the Boeing Vertol Survey in Section 2. This was done by a weighted average based on the number of helicopters operated by each group. (Since there were so few corporate responses, these were combined with the commercial operators.) Civil government agencies operate 17% of the civil helicopter fleet (reference 14), so the percentages in questions 3 and 4 calculated for the government operators were given a weight of 17%, and the percentages for the commercial operators were weighted at 83%. This resulted in the following distributions:

- 32% Acquisition
- 68% Operations and support:
  - 42.8% Direct support maintenance
  - 16.4% Consumables (fuel, oil, lubricants)
  - 30.8% Flight personnel
  - 9.4% Insurance
  - 0.6% Other

The next step was to redistribute the costs into the four categories of R&D, production, operational and support. The 32% of acquisition cost was split into 5% R&D and 27% production, using the relationship shown in reference 9 (4% and 21%). The 68% operations and support cost was distributed as follows:

16.4%	Consumables
30.8%	Flight personnel
9.4%	Insurance
56.6%	of O&S is for operational costs x 68% = 38.48%
68.00%	Operations and support
−38.48%	Operational
29.52%	Support

The split between operations and support costs then is 38% for operational costs and 30% for support costs. This completes the first column of table 6.

The second column is a slightly more detailed distribution of the four basic categories. The 27% of production costs were distributed into 1.35% nonrecurring and 25.65%

recurring according to the ratio in reference 9 (5% and 95%). The 38.48% of operational costs were distributed according to the weighted average ratios from the questionnaire, as follows:

Consumables	16.4%	÷	56.6%	=	29.0%	X	38.48	=	11.15%
Flight Personnel	30.8%	÷	56.6%	=	54.4%	X	38.48	=	20.94%
Insurance	9.4%	÷	56.6%	=	16.6%	X	38.48	=	6.39%

In order that all columns would total, certain liberties were taken in rounding, which do not significantly alter the results.

The 30% of support costs were distributed by subsystem according to relationships established in the reference 32 and 33 reports. These reports give detailed figures by subsystem for the U.S. Army OH-58 and UH-1 aircraft. A weighted average was calculated based on civil helicopter hours flown by the civil versions of these aircraft. Bell 205 and 206 helicopters (9% and 91%, respectively). The distribution was calculated as follows:

Engine	45.3%	X	30%	=	13.59%
Drive	12.4%	X	30%	=	3.72
Rotor	18.2%	X	30%	=	5.46
Airframe	5.6%	X	30%	=	1.68%
					24.45%
Miscellaneous					5.55%
					30.00%

This completes the second column of table 6.

The third column breaks down the cost contributions of column 2 where possible. Using the distribution of production recurring costs shown in Section 3, table 4, the 25.65% of production recurring was separated by subsystem. It was assumed that 98% of consumables costs were for fuel, resulting in the 11.15% for consumables being split as 10.93% fuel and 0.22% oil and lubricants. Insurance costs were distributed according to the accident causal factors contained in reference 1. Finally, subsystem support costs were further broken down according to the distribution by cost contained in reference 7.

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